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Chapter 15

Physical-Chemical Life Support Systems

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Physical-chemical life support systems can be either open, nonregenerative systems or closed, regenerative systems. Open, nonregenerative systems are those in which both the materials essential to sustain human life and the reagents for treatment and contaminant removal are provided as expendable supplies. Such systems are most suited for short-duration missions. In contrast, closed, regenerative systems employ selected chemical processes for recovery of air and water from waste products and for regeneration of contaminant removal adsorbents and other reagents required for future long-duration missions. Food supplies are provided as expendables for both open and closed physical-chemical life support systems. As the duration of human space missions increases and as missions focus on the exploration of environments far from Earth so as to make resupply prohibitive, regenerative physical-chemical life support systems will become increasingly mandatory. For support of such remote, long-duration missions, many attributes, such as reliability, maintainability, and controllability, must become inherent in the life support system design to prevent undue safety hazards to the crew, to maximize crew productivity, and to enhance crew psychological well-being.

I. History and Evolution of Life Support Capability in Spacecraft*

A. Overview

With the evolution of human space flight has come a wealth of knowledge on supporting human life in the hostile environment of outer space. Each successive manned space program has built and improved upon the last, learning from the successes and failures experienced on each mission. As crew size and mission duration and complexity have increased, the spacecraft Environmental Control and Life Support System (ECLSS) has been adapted and improved based on lessons learned from the past.

On early space flights carrying animals, life support systems used stored consumables and simple open-loop systems. On early Soviet flights potassium superoxide (KO_2) was used as an oxygen source and as a carbon dioxide adsorber. The first higher-order living creature placed in Earth orbit was a female mixed-breed dog named Layka, launched on Sputnik II by the Soviet Union on November 3, 1957. Layka's open-loop life support system was a hermetically sealed, air-conditioned compartment complete with food and water. A typical U.S. design was that used to sustain a monkey named Gordo, who rode a ballistic path through space in the nose cone of a Jupiter missile in December 1958. Carbon dioxide was absorbed by pellets of baralyme, and the breathing gas was compressed oxygen from a cylinder. Temperature control was partially achieved by insulating layers of metal foil and fiberglass, and water vapor was absorbed by a porous material. The waste management system consisted of a diaper on the monkey. Gordo was provided neither food nor water.[1]

Support of human life in space was the next ECLSS goal. Life support systems have succeeded in supporting human life on the Moon and for mission durations over a year. The design of ECLSSs for future manned missions must begin with a knowledge of past designs. This knowledge should come from the manned space programs of both the United States and the Soviet Union. Both countries have been pursuing the manned exploration of space for more than 30 years, resulting in a considerable experience base.

A summary of the ECLSS on U.S. manned spacecraft is presented in Table 1 for Mercury, Gemini, Apollo, Skylab, Spacelab, Space Shuttle, and Space Station. A summary of the ECLSS on Soviet spacecraft is presented in Table 2 for Vostok, Voskhod, Soyuz, Salyut, and Mir.

B. ECLSS Design History on U.S. Spacecraft

Manned space flight in the United States began with Alan Shepard's 15-min suborbital flight aboard the Freedom 7 Mercury-Redstone 3 spacecraft on May 5, 1961. Thirty years later the United States is planning to launch a space station designed to remain in orbit for 30 years. U.S. ECLSS design

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Table 1a - ECLSS on U.S. Spacecraft (Modified from Ref. 41 with permission of Society of Automotive Engineers, © 1990)

Subsystem	Mercury	Gemini	Apollo CM	Apollo LM	Skylab	Orbiter	Spacelab	Space Station
Atmosphere Revitalization								
CO_2 Removal	Two LiOH canisters operated in parallel, with airflow through only one. After the first canister was spent, airflow was diverted through the second, and the spent one was replaced.	Similar to Mercury design	Similar to Mercury design	Similar to Mercury design	Two canister molecular sieve. Each regenerative canister contained Zeolite 5A. CO_2 was vacuum desorbed to space.	Similar to Mercury design	Similar to Mercury design. Eight canisters included on each mission.	Four-bed molecular sieve. Includes two regenerative desiccant beds to remove water and two regenerative Zeolite 5A molecular sieve beds. CO_2 heat and pressure desorbed to an accumulator before being fed to Sabatier reactor.
Gas Recovery/ Generation	None	None	None	None	None	None	None	Sabatier reactor for CO_2 reduction. Static Feed Water Electrolysis (SFWE) for oxygen generation. The SFWE uses a KOH electrolyte.
Trace Contaminant Control	Activated charcoal located in LiOH canisters upstream of the LiOH. Filters removed airborne particulates.	Similar to Mercury design	Similar to Mercury design	Similar to Mercury design	Activated charcoal canister located in the molecular sieve unit. Filters removed airborne particulates. Venting of atmosphere between missions avoided contaminant buildup.	Activated charcoal downstream of the LiOH. CO converted to CO_2 by ambient temperature catalytic oxidizer (ATCO). Filters removed airborne particulates.	Activated charcoal canister located in transfer tunnel between Spacelab and Orbiter. CO converted to CO_2 by ATCO. Filters removed airborne particulates.	Activated charcoal with a high-temperature catalytic oxidizer. Filters remove airborne particulates.
Trace Contaminant Monitoring	CO sensor[2]	No on-orbit monitoring	No on-orbit monitoring	No on-orbit monitoring	Draeger tubes monitored buildup of CO and other trace contaminants.[28]	No on-orbit monitoring	No on-orbit monitoring	A CO monitor and a gas chromatograph/ mass spectrometer (GCMS) for detecting contaminants.

Table 1b - ECLSS on U.S. Spacecraft

Subsystem	Mercury	Gemini	Apollo CM	Apollo LM	Skylab	Orbiter	Spacelab	Space Station
Water Recovery & Management								
Water Supply Quality	Potable only	Potable only	Potable only	Potable only	Potable only	Potable only	Not applicable	Potable only
Water Processing	None. Vent waste water.	None. Vent waste water	None. Stored waste water and vented excess, or sent excess to evaporators for additional cooling.	None. Stored waste water. No overboard dumpling of wastes on lunar surface.	None. Stored waste water in tanks and vented when tanks full.	None. Store waste water in a tank and vent waste when tank is full.	Not applicable	Urine-vapor compression distillation (VCD). Potable and wash water multifiltration using sorbent beds.
Water Monitoring	No on-orbit monitoring	No on-orbit monitoring		No on-orbit monitoring	Iodine sampler. Water samples fixed with a linear starch reagent and compared to photographic standards.	No on-orbit monitoring	Not applicable	On-line TOC, pH, iodine concentration, and conductivity monitor for each water processor. Off-line batch microbial and chemical monitoring using mass spectrometry; filter cultures; and gas, liquid, and ion chromatography.
Water Storage and Distribution	One tank with flexible bladder. Squeezing an air bulb pressurized the bladder to deliver water (sphygmomanometer).[3]	One 7.3 liter tank containing a bladder pressurized with oxygen to deliver water. Empty tank was refilled from reserves in the service module.	Fuel cell by-product was principal source of potable water. Palladium and silver removed dissolved H_2. Potable tank used a bladder pressurized by oxygen to deliver water	Three (four on Apollo 15, 16 17) potable tanks, each with a bladder pressurized by nitrogen to deliver water. Potable water also used to cool spacecraft and extravehicular mobility units.	Ten cylindrical 600 lb. capacity stainless steel tanks fitted with pressurized steel bellows to deliver the water. One 26 lb capacity potable tank.[28]	Four 168 lb capacity stainless steel tanks fitted with metal bellows pressurized by N_2. Drinking water is from the fuel cell by-product.	Not applicable	Tank design similiar to the Orbiter, except air is used instead of N_2 to pressurize the metal bellows.

Table 1c - ECLSS on U.S. Spacecraft

Subsystem	Mercury	Gemini	Apollo CM	Apollo LM	Skylab	Orbiter	Spacelab	Space Station
Water System Microbial Control	Water quality depended on the quality of the public water system in Cocoa Beach, FL. Bacterial control depended on the residual disinfectant (chlorine) in the public supply.[29]	Chlorine added to the water before launch	Chlorine at a concentration of 0.5 mg/l maintained by adding 22 ml sodium hypoclorite solution every 24 h.	Iodine added before launch. No on-orbit biocide addition. Pre-flight analysis performed to predict when the iodine concentration would fall below 0.5 mg/l during mission. When this predicted time was reached a bacteria filter was added.	Iodine maintained between 0.5 and 6.0 mg/l by periodic injection of a 30 g/l potassium iodide solution.	Iodine from microbial check values (MCV). MCV passively adjusts iodine concentration between 1 and 2 mg/l.	Not applicable	Iodine from microbial check values (MCVs). Heat sterilization at 120° C for 20 min planned as part of water processing cycle.
Temperature and Humidity Control								
Atmosphere Temperature and Humidity Control	Separate suit and cabin condensing heat exchangers (CHX). Mechanically activated sponge water separator removed water from the CHX. Condensate rejected to water boiler for heat rejection. Pilot regulated suit and cabin temperature by adjusting water flow rate through the suit and cabin HX's with a needle valve.[30]	Suit CHX primary method for cabin temperature and humidity control. Wicks removed water from CHX by capillary action. Water-ethylene glycol coolant.	Separate suit and cabin CHX's. Wicks removed water from CHX by capillary action. Manual throttling of O_2 / coolant flow rate in suit loop to control temperature. Heat transport loop with MCS-198 coolant primary method for heat rejection.[31]	Water circulated through pressure garment assembly to cool astronaut. Water-ethylene glycol coolant.	Four CHXs, two operating at all times. Coolanol 15 coolant.	Centralized cabin liquid-air CHX using water coolant. Air bypass ratio around CHX adjusted to control temperature. Condensate removed by slurper bar and centrifugal separator.	Similar to Orbiter design	Similar to Orbiter design
Cabin Ventilation	Cabin fan	Cabin fan	Cabin fans. The fans were noisy, so the crew only operated them during short specified periods.[32]	Cabin fan	Three ventilation ducts with four fans each. Air distributed from circular diffusers with dampers mounted flush with the floor, and from rectangular outlets with dampers and adjustable flow vanes. Three portable fans with adjustable diffusers.	Cabin fan with ventilation ducts	Cabin fan	Cabin fans and separate local area ventilation fans

Table 1d - ECLSS on U.S. Spacecraft

Subsystem	Mercury	Gemini	Apollo CM	Apollo LM	Skylab	Orbiter	Spacelab	Space Station
Equipment Cooling	Cold plates and air cooling. Cabin gas absorbed heat generated by equipment and was cooled when it passed through the cabin CHX.	Similar to Mercury	Similar to Mercury	Similar to Mercury	Similar to Mercury	Air cooling, cold plates, and air/liquid equipment dedicated HXs. Avionics air loop separate from cabin loop, except in aft flight deck.	Air cooling, cold plates, liquid/liquid equipment dedicated HXs. Avionics air loop separate from cabin loop. Flow control valves set manually before flight.	Air cooling, cold plates, and equipment dedicated HXs. Avionics air loop separate from cabin loop in the habitation and laboratory modules, but combined with cabin loop in nodes and logistics module. Air flow controlled automatically.
Atmosphere Control and Supply								
Atmosphere Composition	100% O_2 at 5 psia (34.5 kPa)	100% O_2 at 5 psia (34.5 kPa)	100% O_2 at 5 psia (34.5 kPa). 60% O_2, 40% N_2 atm. during launch.	100% O_2 at 5 psia (34.5 kPa)	Mixed O_2/N_2 at 5 psia (34.5 kPa) total pressure. 72% O_2, 28% N_2 by volume.	Mixed O_2/N_2 at 14.7 psia (101 kPa) total pressure. 21.7% O_2, 78.3% N_2.	Mixed O_2/N_2 at 14.7 psia (101 kPa) total pressure. 21.7% O_2, 78.3% N_2.	Mixed O_2/N_2 at 14.7 psia (101 kPa) total pressure. 21.7% O_2, 78.3% N_2 volume.
Gas Storage	O_2 stored as a gas at 7500 psi (51.7 MPa) in two 1.8 kg. capacity tanks made of 4340 carbon steel with electrodeless nickel plating. One tank was primary supply, the other was backup.[30]	O_2 stored as a supercritical cryogenic fluid at 850 psi (5.86 MPa) in one spherical tank. Separate tank supplied the fuel cells. Two secondary cylindrical 5000 psi O_2 bottles. One small O_2 bottle attached under each ejectable seat for emergencies.[31]	O_2 stored as a supercritical cryogenic fluid at 900 psi (6.20 MPa) and 180 C_2 in two 145 kg capacity spherical Inconel dewar tanks. Tanks were common for ECLS and power systems. Tanks discarded during reentry, then O_2 was supplied from 1.7 kg capacity surge tank.[32]	21.8 kg of O_2 stored as a gas at 2700 psi (18.6 MPa) in descent stage. In ascent stage O_2 stored as a supercritical cryogenic fluid at 850 psi (5.86 MPa) in two Inconel bottles.[32]	O_2 and N_2 stored as gases at 3000 psi (20.7 MPa) in six bottles each, for a total of 2779 kg of O_2 and 741 kg of N_2	N_2 and O_2 stored as gases at 3300 psi (22.8 MPa). Four spherical N_2 tanks and one emergency O_2 tank. Metabolic O_2 supplied by the power reactant storage and distribution system, which uses supercritical cryogenic storage tanks.	N_2 stored as a gas at 3300 psi (22.8 MPa) in a spherical tank. O_2 source is a 100 psi (689 kPA) line from Orbiter.	Cryogenic stores of O_2 and N_2

Table 1e - ECLSS on U.S. Spacecraft

Subsystem	Mercury	Gemini	Apollo CM	Apollo LM	Skylab	Orbiter	Spacelab	Space Station
Waste Management								
Fecal/Urine Handling	In-situ urine collection bag stored onboard. No provisions for fecal handling. No provisions for urine handling on first Mercury mission.	Feces collected in bags and stored. Bags taped to buttocks. Urine collected using urine transfer system, consisting of a rubber cuff connected to a flexible bag. Urine could be directed to boiler tank to assist with spacecraft heat rejection.	Feces collected in bags and stored. Bags taped to buttocks. Bags were needed to mix liquid bactericide with feces. Before Apollo 12, Gemini urine collection system was used. After Apollo 12, urine receptacle assembly, which did not contact the crewman, used. Urine vented. [32]	Fecal containment system identical to Apollo CM system. Primary difference was no overboard dumping of urine on lunar surface.	Feces collected in gas permeable bags attached under a form-fitting seat, then vacuum dried and stored. Urine collected using individual receivers, tubing, and disposable collection bags. [28]	Commode-Urinal - Feces collected in the commode storage container, vacuum dried, and held. Urine sent to a waste water tank which is vented when full.	Utilizes Orbiter facilities	Commode/Urinal- Feces collected in a bag and compacted in a cylindrical canister for biodegradation. Urine sent to the vapor-compression distillation unit to be recovered as potable water.
Fire Detection and Suppression								
Suppressant	Water from the food rehydration gun.[14] Capability to depressurize cabin by manually opening cabin outflow valve.	Similar to Mercury design. Maximum of three cabin depressurizations could be accommodated by on-board oxygen supply.	Water from food rehydration gun and a portable aqueous gel (hydroxymethyl cellulose) extinguisher, which could expel 0.06 m of foam in 30 s. Capability to depressurize cabin	Similiar to Apollo CM design	Portable aqueous gel similar to Apollo. Capability to depressurize cabin.	Halon 1301. Two Halon tanks with distribution lines in each avionics bay. three portable Halon extinguishers. Capability to depressurize cabin.	Halon 1301. Halon bottle with distribution lines located in each equipment rack. Two portable Halon extinguishers. Capability to depressurize cabin.	CO_2 . Centralized CO_2 bottles with distribution lines to powered equipment racks. Portable CO_2 extinguishers. Capability to depressurize cabin.
Detection	Crew senses [33]	Crew senses	Crew senses	Crew senses	Ultraviolet detectors	Ionization smoke sensors	Ionization smoke sensors	Photoelectric smoke detectors and UV/IR/visual flame detectors.

Table 2a - ECLSS on Soviet Spacecraft (Modified from Ref. 41, used with permission Society of Automotive Engineers, © 1990)

Subsystem	Vostok	Voskhod	Soyuz	Salyut	Mir 1
Atmosphere Revitalization					
CO_2 Removal	CO_2 removed through reaction with potassium superoxide (KO_2) in the oxygen regenerator (forming potassium carbonate and oxygen).[3]	Similar to Vostok design.	Similar to Vostok design. LiOH beds used to absorb about 20% of CO_2.[35]	Similar to Soyuz design.	Four-bed molecular sieve. Two regenerative silica gel desiccant beds and two regenerative molecular sieve beds containing adsorbent similar to Zeolite 5A. LiCl canisters used as backup.[36]
Gas Recovery/ Generation	Nonregenerative chemical cartridges of KO_2. KO_2 reacted with water to produce O_2 and KOH.[3]	Similar to Vostok design	Similar to Vostok design	Similar to Vostok design	CO_2 not utilized. CO_2 vacuum desorbed overboard. Water electrolysis using a KOH electrolyte for oxygen generation. Electrolyzed water from recovered urine supplemented by onboard stores.[36]
Trace Contaminant Removal	Activated charcoal and filters. Contaminants also removed through reaction with constituents in oxygen regenerator.[3]	Similar to Vostok design	Similar to Vostok design	Activated charcoal, high efficiency fiberglass filter, and catalytic chemical absorbents. Oxygen regenerator also removes contaminants[37]	Regenerated charcoal beds and catalytic oxidizers. Charcoal beds regenerated by vacuum for 6 hours once every 10 days. Impurities vented.[37]
Trace Contaminant Monitoring	Gas analyzer determined percent composition of O_2 and CO_2 in cabin atmosphere. No other on- orbit atmosphere monitoring.[3]	Similar to Vostok design	Similar to Vostok design	Similar to Vostok design. Several gas analyzers distributed around the station.[37]	Similar to Salyut design
Water Recovery and Management					
Water Supply Quality	Potable only	Potable only	Potable only	Potable only	Potable, hygiene, and electrolysis grade
Water Processing	None	None	None	Salyut 6, 7 - Potable water recovered from condensate. Waste water pumped into storage columns containing ion exchange resins and activated charcoal, then sent through filters containing fragmented dolomite, artificial silicates, and salt. Minerals added, including calcium, magnesium, bicarbonate, chloride, and sulfate.[37]	Three water purification systems: 1. Condensate recovered by same process used on Salyut 6, 7. 2. Wash/kitchen water recovered by system of filters and ion exchange resins. 3. Electrolysis water recovered from urine by vapor diffusion distillation.[36]
Water Quality Monitoring	None	None	None	None	Water analyzers[36]

Table 2b - ECLSS on Soviet Spacecraft

Subsystem	Vostok	Voskhod	Soyuz	Salyut	Mir l
Water Storage and Distribution	Water held in a container made of two layers of elastic polyethylene film, hermetically sealed inside a metal cylinder. Low pressure created by the crewman's mouth induced water flow from the container. Each crewman allotted 2.2 l/day of water.[3]	Similar to Vostok design	Similar to Vostok design	Rodnik ("spring") system supplies water from tanks with a total volume of over 400 liters [37]	Similar to Salyut design. Tanks use pressurized bladders to deliver water.[36]
Water Supply Microbial Control	Silver preparation added to water, which was boiled before launch [3]	Similar to Vostok design	Similar to Vostok design	Water is heated and ionic silver is introduced electrolytically to a concentration of 0.2 mg/l [37]	Similar to Salyut design
Temperature and Humidity Control					
Atmosphere Temperature and Humidity Control	Liquid-air condensing heat exchanger. Condensate trapped by porous wicks between heat exchanger tubes. Temperature adjusted by automatic regulation of air flow rate through heat exchanger. Cosmonaut set temperature and humidity. Temperature range between 12–25 °C, relative humidity between 30%–70%. Humidity was controlled by the temperature of a coolant and an additional dehumidifier containing anhydrous silica gel and activated charcoal impregnated with LiOH. Dehumidifier operated cyclically. Air inlet to dehumidifier opened after humidity rose above 70%. Air inlet automatically closed when humidity reached 35 ± 5%.[38]	Similar to Vostok design.	Liquid-air condensing heat exchanger. Temperature adjusted by automatic regulation of air flow rate through heat exchanger. Liquid coolant was a water/ethylene glycol mixture. Cosmonaut set temperature and humidity of craft. Temperature range between 12–25 °C, relative humidity between 30–70%. Humidity controlled primarily by condensing heat exchanger. Condensate trapped by porous wicks between the heat exchanger tubes. Primary role of the chemical water adsorbants was control of the oxygen production rate of O_2 regenerator.[3]	Liquid-air condensing heat exchanger. Temperature set by cosmonaut between 15–25 °C. Coolant was antifreeze-type fireproof liquid. Porous wicks trapped moisture between heat exchanger tubes. Condensate collected in a moisture trap and pumped out manually by the cosmonauts.[39]	Liquid-air condensing heat exchanger. Two internal thermal control loops - a cooling loop and a heating loop - charged with "Temp" coolant. Redundant piping system included with each loop. Loop temperature controlled automatically.[36]
Cabin Ventilation	Cabin fan	Cabin fan	Cabin fan	Cabin fan. Cosmonauts controlled air flow rate between 0.1–0.8 m/s.[37]	Fans pull air through ducts to exchange gas between modules.[40]

Table 2c - ECLSS on Soviet Spacecraft

Subsystem	Vostok	Voskhod	Soyuz	Salyut	Mir 1
Equipment Cooling	Avionics is cooled by air that was passed through the heat exchanger	Similar to Vostok design	Similar to Vostok design	Similar to Vostok design	Avionics cooled by heat exchangers and air pulled from cabin. Condenser with freon removes moisture that condenses on the equipment.[36]
Atmosphere Control and Supply					
Atmosphere Composition	Sea-level atmosphere - O_2 /N_2 mixture at 14.7 psi (101 kPa)	Sea-level atmosphere- O_2 /N_2 mixture at 14.7 psi (101 kPa)	Sea-level atmosphere. O_2 /N_2 mixture at a total pressure between 13.7–16.4 psi (94.4–113 kPa), with ppO_2 between 2.7 and 3.9 psi (10.5–15.2 kPa).	Sea-level atmosphere. O_2 /N_2 mixture at a total pressure between 13.5–18.5 psi (93.1–128 kPa), with ppO_2 between 3.1–4.6 psi (21.4–31.7 kPa).	Sea-level atmosphere. Up to 78% N_2, 21-40% O_2. Maximum ppO_2 is 6.8 psi (46.9 kPa).
Gas Storage	Oxygen supply stored chemically Emergency tanks of high pressure oxygen and air for suit ventilation and cosmonaut breathing. Cosmonaut's suit could be pressurized if the cabin depressurized. No N_2 storage. Cabin hermetic seal was designed for zero leakage.[40]	Similar to Vostok design	Similar to Vostok design	Oxygen supply stored chemically. Cylinders of compressed air for leakage makeup. No separate N_2 or O_2 storage.[38]	Backup oxygen stored chemically as $NaCeO_7$. N_2 is stored as a high pressure gas. Oxygen is produced from water electrolysis.[37]
Waste Management					
Fecal/Urine Handling	Urine and feces entrained in air stream and collected. Design of the urine/feces receiving unit permitted simultaneous collection of urine and feces when clothed in a space suit.	Similar to Vostok design	Similar to Vostok design	Each defecation is collected in a bag which is then stored in sealed metal containers which are ejected to space, about once a week. The urine collector, separate from the main commode, is a cup-and-tube device with a disposable plastic insert and filter.	Commode for urine and feces collection. Urine sent to water recovery processor after passing through an air/liquid separator.

Table 2d - ECLSS on Soviet Spacecraft

Subsystem	Vostok	Voskhod	Soyuz	Salyut	Mir 1
Fire Detection and Suppression					
Suppressant	Cabin depressurization capability	None	Same as Vostok design	Same as Vostok design	Portable extinguishers. Crew can open valves to extinguish fires in inaccessible areas. Cabin depressurization capability.[36]
Detection	Crew senses	Crew senses	Crew senses	CO_2 detectors doubled as smoke detectors[37]	Optical sensors[36]

has come a long way since that first Mercury flight, having since supported human life on Gemini, Apollo, Skylab, Spacelab, Space Shuttle, and soon on Space Station. Table 1 details the primary facets of ECLSS design for each of these U.S. spacecraft. The dates listed with each spacecraft give the period when it was being used for space missions.

1) Mercury (1960–1963)—The objectives of the Mercury project were to place manned spacecraft in Earth orbit, explore human reactions in orbit, test the possibilities of manual spacecraft control by the pilot, and safely recover astronauts and capsules from space. Mercury was a pressurized one-man capsule in the shape of a bell, with 1.56 m^3 of habitable space for the astronaut.[2] The Mercury ECLSS is composed of pressure suit and cabin subsystems. The pressure suit subsystem was primarily responsible for revitalizing the astronaut's atmosphere supply and for controlling his/her temperature and humidity level. The cabin subsystem controlled cabin ventilation, cabin temperature (the cabin heat exchanger did not remove water vapor), and atmospheric pressure. The space suit was normally unpressurized during flight.

2) Gemini (1964–1966)—The Gemini project, an extension of the Mercury project, was the second phase of the U.S. plan to land humans on the Moon. Its objectives were to test crew and capsule behavior for a nonstop 14-day orbit, develop the capability to rendezvous and dock with other spacecraft, perform extravehicular activities, develop methods for controlling spacecraft reentry flight paths, and provide a basis for scientific experimentation. Gemini was a pressurized two-man capsule with 2.26 m^3 of habitable space for the astronauts.[2] As with Mercury, the Gemini ECLSS was divided into the pressure suit and cabin subsystems. Gemini improvements over the Mercury ECLSS included supercritical oxygen storage instead of high-pressure storage, an integrated heat exchanger/water separator, and a mechanically activated sponge-type water separator.

3) Apollo (1968–1972)—The objectives of the Apollo project were to land a human on the Moon and return him/her safely to Earth, explore the Moon from the lunar surface and from lunar orbit, and demonstrate that humans can move about and work in an alien environment. The total Apollo space vehicle included two separate life support systems, one on the command module (CM) and one on the lunar module (LM). The CM ECLSS occupied 0.25 m^3 of the cabin and was capable of operating for 14 days. Oxygen and potable water from fuel cells were supplied from the Apollo service module, which was attached to the base of the CM. Launch safety was increased by using a 60 percent oxygen (O_2) and 40 percent nitrogen (N_2) cabin gas mixture during prelaunch and launch periods, although the suit circuit remained at 100 percent O_2. The ascent stage of the Apollo LM was a pressurized two-man craft with 4.5 m^3 of habitable space.[2] The third astronaut from the CM remained in the CM in circumlunar parking orbit until the ascent module returned from the Moon. In contrast to the Apollo CM ECLSS, the LM ECLSS had potable water from storage tanks instead of fuel cells, no overboard venting of urine on the lunar surface, and iodine bactericide instead of chlorine to avoid corrosion problems anticipated between chlorine and the LM sintered nickel sublimator plates. Unlike the situation in all previous spacecraft, there were no seats in the LM, so the astronaut had to be accommodated from a standing position.

4) Skylab (1973–1974)—The objectives of Skylab, the first U.S. space station, were to study the effects of long-duration space flight on humans; study the Earth, Sun, and stars; and perform experiments in a microgravity environment. Skylab was a three-person laboratory with a total habitable volume of 361 m^3 (Ref. 2). The crew lived and worked in the two-level orbital workshop, although most of the ECLSS equipment was located in the airlock module. New ECLSS techniques on Skylab included a mixed O_2 and N_2 atmosphere and two-canister molecular sieves instead of lithium hydroxide (LiOH) canisters to remove carbon dioxide (CO_2), a method of monitoring iodine concentration in the water supply, the storage of urine samples in a freezer for analysis on Earth, and ultraviolet fire detectors. Between missions, when Skylab was unoccupied, the atmosphere was depressurized to 13.8 kPa and allowed to decay down to 3.45 kPa until the next group of astronauts arrived. Depressurization removed trace contaminants from the cabin to reduce the chance of fire.

5) Space Shuttle Orbiter (1981–present)—The objective of the Space Shuttle Program is to replace expendable launch vehicles with a reusable transport to increase accessibility to space at a relatively low cost. Shuttle missions support private and commercial ventures in space, including the eventual construction of a permanent space station. The Orbiter is designed to carry an average crew of seven for a nominal mission of 7 days in a total habitable volume of 74 m^3 (Ref. 2). The Orbiter became the first U.S. spacecraft to use a standard sea-level atmosphere—a gas mixture of 22 percent O_2 and 78 percent N_2 at a total pressure of 101 kPa. Other Orbiter ECLSS innovations included Halon 1301 fire suppressant; microbial check valves to passively adjust iodine concentration in the potable water supply; and a commode for fecal collection and storage, to be used instead of simple bag collection.

6) Spacelab (1983–present)—The cylindrical Spacelab laboratory module, situated in the Space Shuttle cargo bay during a Spacelab module mission, provides a pressurized, shirt-sleeve environment for performing experiments in microgravity. Most of the Spacelab ECLSS is very similar to the Orbiter system and depends on the Orbiter for its metabolic O_2 supply. Cabin air is exchanged with the Orbiter through the Spacelab transfer tunnel. An avionics air loop, separate from the cabin air loop, is used for air-cooling rack-mounted instrumentation. Spacelab can remain operational throughout a Space Shuttle mission.

7) Space Station—The Space Station will serve as a research laboratory in space and potentially as a staging base for missions to the Moon, Mars, and beyond. The description of Space Station ECLSS below and in Table 1 is for a crew of eight for the fully configured Space Station. Space Station

will be composed of a number of pressurized elements, including laboratory modules, habitation modules, nodes, an airlock, and a logistics module. The planned ECLSS design will provide a closed system for air and water and will be more complicated than any ECLSS of the past, all of which were basically open systems. CO2 will be reduced to recover the useful O_2 atoms in the form of water. O_2 will be produced by water electrolysis, eliminating the need for O_2 resupply. Hygienic wastewater, urine, condensate, and CO_2 reduction water will be recycled to keep water resupply to a minimum. Long-term operation must accommodate simple on-orbit maintenance requiring little crew time. The above description pertains to a single design variant of Space Station. Some of the information presented in Table 1 may change before launch of the first station element. As the present work goes to press, the design of the entire station is undergoing review and revision and may change drastically.

C. ECLSS Design History on U.S.S.R. Spacecraft

The first human being in space was Yuriy Alexeyevich Gagarin, a Soviet Air Force pilot. Launched into Earth orbit aboard a Vostok capsule by an A-l rocket on April 12, 1961, Gagarin made one orbit of the Earth, completing the 108-min mission with little difficulty. The U.S.S.R. has far more experience with manned space flight than all other nations combined, particularly in the realm of long-duration missions. A number of cosmonauts have completed stays in space of well over 300 days. Since 1971, the Soviets have launched eight space stations, including the currently orbiting Mir station. Table 2 describes the ECLSS designs on the Soviet Vostok, Voskhod, Soyuz, Salyut, and Mir spacecraft. In Russian, the ECLSS is referred to as the Sistema Obespecheniya Zhiznedeyatelnosti (SOZh), meaning "Life Support System."

1) Vostok (1960–1963)—The spherical Vostok, with a habitable volume of approximately 3 m^3, was the first spacecraft to carry a human into space. The objectives of the Vostok program were to test human behavior under microgravity, test high acceleration and deceleration levels (8–10 g), test and further develop ground-controlled automatic spacecraft guidance, and make astronomical and geophysical observations.[2] The Vostok ECLSS was a simple semiclosed system with a 101-kPa air atmosphere. Cabin ECLSS equipment was responsible for CO_2 removal and the control of cabin odor, humidity, ventilation, temperature, and air supply.[3] The cosmonaut wore a space suit that was ventilated by cabin air and did not have the capability for air purification or humidity control. In an emergency, the suit could be supplied with air and O_2 from tanks mounted on the Vostok exterior.

2) Voskhod (1964–1965)—The spherical Voskhod capsule was basically an improved version of the Vostok with a rearranged interior to accommodate three crewmembers. To help make room for the cosmonauts, Voskhod became the first spacecraft in which the crew did not wear space suits. Objectives of the Voskhod program were to gather data on group crews and study human behavior outside the capsule.[2] Voskhod 2 was equipped with two space suits and an inflatable decompression chamber, from which the first space walk was performed.

3) Soyuz/Soyuz T (1967–present)—Soyuz was designed primarily for docking with other space vehicles. Objectives of the Soyuz program were to perfect docking and crew transfer between capsules and Salyut stations, practice craft orbital transfer, and perform scientific observations and experiments.[2] Designed for 7-day missions, the Soyuz was a three-man vehicle with two pressurized compartments, one for living and working and the other for descent. Soyuz cosmonauts did not wear pressurized suits. After Soyuz 11, the crew was reduced to two to make room for pressurized suits. The hermetically sealed Soyuz cabin was designed for zero leakage. Soyuz T, a modified version of Soyuz, which retains the basic size and shape of the Soyuz craft, has a redesigned interior to accommodate three space-suited cosmonauts. Soyuz spacecraft are still used to ferry cosmonauts to and from the orbiting Mir space station.

4) Salyut Space Stations (1971–1986)—Salyut was the first spacecraft designed for extended missions in space and, thus, became the world's first space station. Since the beginning of the Salyut program, seven Salyut stations were placed in orbit. With the overriding goal of establishing a permanent presence in space, Salyut was considered the cornerstone of Soviet policy aimed at establishing human colonies on the Moon and Mars.

Designed for a crew of five, Salyut consists of three inseparable modules with a total usable volume of about 100 m^3 (Ref. 2). Each successive Salyut improved on the previous station, although the basic configuration remained the same. The ECLSS remained predominantly the same on the Salyut stations until Salyut 6, when a water regeneration system was added to recover condensate and wash water.

5) Mir Space Station (1986–present)—Currently in Earth orbit, the Mir space station is the third generation of Soviet orbital stations, although the design of its core is basically similar to that of Salyut 7. The Mir core, designed for a crew of six in a habitable volume of about 150 m^3 (Ref. 4), is the first space station designed to accommodate growth by the addition of modules. Mir uses several regenerative ECLSS technologies. O_2 is produced by water electrolysis, and CO_2 is removed by a four-bed molecular sieve system and vented to space. Wastewater is also recovered. Research is currently in progress to further advance the Mir ECLSS to increase the closure.

D. Summary

A summary of the ECLSSs on past, present, and planned spacecraft has been presented. The tabular summary allows for ready comparison of spacecraft ECLSS design and depicts how the ECLSS has evolved (and continues to evolve) from the early open systems to the nearly closed ECLSS space station systems planned for the 1990s. As endeavors in manned space flight continue, the knowledge of how to sustain human life in space will continue to advance. The development of techniques for regenerating atmosphere and water will reduce dependence on resupply from Earth, increasing the chances for long-duration space voyages far from home. Future ECLSSs may be completely closed, with as little dependence as possible on outside sources for life-sustaining supplies. Closed-loop ECLSSs will pave the way for human settlements on the Moon and beyond, where regular resupply from Earth may not be feasible. ECLSS evolution will make the permanent human occupation of space more than simply a dream.

II. Common and Specific Mission Requirements

A. Overview

The basic architecture of the ECLSS can be divided into requirements that are common and those that are mission specific. An example of a common requirement is the cabin air ventilation flow range. An example of a mission specific requirement is provision of food supply refrigeration.

In this discussion, we will use the planned Space Station ECLSS as an example. The ECLSS is composed of six major subsystem groups,[5] which are interlinked with each other as well as with external interfaces. The definition of the ECLSS can be given by defining the six subsystem groups: temperature and humidity control (THC), atmosphere control and supply (ACS), atmosphere revitalization (AR), water recovery and management (WRM), waste management (WM), and fire detection and suppression (FDS).

The subsystem groups can further be described by listing the functions performed in them. THC consists of air temperature control, humidity control, ventilation, equipment air cooling, thermal conditioning, and airborne particulate and microbial control. ACS encompasses O_2N_2 storage, distribution and resupply, venting, relief, and dumping, as well as O_2N_2 partial and total pressure control. AR consists of CO_2 removal, CO_2 reduction, O_2 generation, and trace chemical contamination control and monitoring. WRM comprises urine water recovery, wash water processing, potable water processing, water storage and distribution, and water quality monitoring. WM encompasses fecal waste collection, processing or storage, and fecal return waste storage and handling. FDS comprises fire detection and fire suppression.

B. General Requirements

Requirements which the ECLSS must meet fall into four basic categories. The first and probably the most critical category is related to crew health and is defined by medical personnel. The next category is related to environmental control for equipment. The third involves general service provisions, which are typically dictated by either programmatic or system design considerations or overall system efficiency studies. The final category involves requirements derived from the extrapolations of other requirements in the first three categories or derived to protect ECLSS equipment.

The ECLSS requirements must be based upon the nominal human mass balance, as defined in Table 3. This table shows both input and output masses for food, liquids, and gases. Variations will depend primarily on activity levels and food water content. Table 4 shows a typical set of overall atmospheric requirements with footnotes to elaborate. Those requirements not specified here include electrical and electronic aspects (e.g., grounding and power stability specifications), material requirements (e.g., flammability and corrosion), structural and stress requirements (e.g., proof and burst design levels), special safety issues (e.g., sharp edge elimination and locknut safety wiring), noise or vibroacoustic requirements, and electromagnetic interference requirements.

C. Subsystem Group Requirements

The THC subsystem group must provide THC functions over the entire pressurized volume under normal operations. Adequate ventilation must be provided in all habitable areas, including intraelement and interelement airflow. As an integral part of the air circulation, both particulate and microbial control must be ensured. The ECLSS must be capable of providing air cooling to permanently mounted equipment (especially in enclosures such as racks). Refrigeration and freezer capability must be provided for food and other items requiring low-temperature storage. Table 4 gives specific temperature, humidity, and ventilation flow requirements. It should be noted that the system will be capable of temperature selection and control by the crew to a set-point value anywhere in the range of achievable temperatures plus or minus 1 °C.

Ventilation flow is provided to all human-occupied zones in a range of 5–13 m/min, with expectations of near-perfect mixing and with no short circuiting of flow, or dead spots, in the human-occupied volume. In addition, surface temperatures must be maintained above the local dew point to avoid condensation. Refrigeration is typically provided when non-thermally-stabilized food is utilized. The temperature of refrigeration is 5 °C. Typically, food freezers operate at –32 °C; however, lower temperature operating regimes may be desirable when the freezer is used for other purposes, such as quick freezing of biological specimens or storage for specialized science purposes. Table 4 also details microbial and particulate requirements. Although one typical set of particulate limits is given, the limits are generally a variable that may differ considerably from mission to mission.

ACS subsystem group functions provide methods of regulating and monitoring the air total pressure and selected partial pressures. Storage, distribution, and supply of O_2 and N_2 are provided. Vent, relief, and overboard bleed or dump capabilities are also provided as an ECLSS service. Sufficient N_2 for makeup of leakage and required repressurization must be provided, along with other support requirements, as necessary. O_2 for leakage, as well as metabolic makeup, with added resources as necessary to support contingencies, is a normal ECLSS-supplied service. Table 4 also provides total

Table 3 Nominal crewmember metabolic balance, nonextravehicular activity (kg/man-day)[a]

Input		Output[b]	
Food solids	0.62	Waste solids	0.11
		Urine	0.06
		Feces	0.03
		Sweat	0.02
Liquids (water)	3.52	Waste liquids	3.86
Drink	1.61	Urine	1.50
Food preparation	0.76	Sweat and respiration	2.27
Food H_2O content	1.15	Fecal H_2O	0.09
Gases	0.83	Gases	1.00
O_2	0.83	CO_2	1.00
Total	4.97	Total	4.97

[a]Assuming metabolic rate = 2700 kcal/man-day and respiration quotient = 0.87.
[b]The food and O_2 inputs are metabolized by the crewmember to produce 0.34 kg/man-day of metabolic water (reflected in the waste liquids total) and 0.45 kg/man-day of CO_2.

Table 4 Atmosphere requirements for Space Station (90-day)

Atmospheric requirement	Units	Operational	Emergency
CO_2 partial pressure	mmHg	3 max.	12 max.
Temperature	deg C	19–27	15–33
Dew point[a]	deg C	4.4–10	4.4–10
Ventilation	m/min	5-13	1.5–60.0
O_2 partial pressure[b]	kPa	19.5–22.4	15.6–23.5
Total pressure	kPa	98.6–101.3	98.6–101.3
Dilute gas	–	N_2	N_2
Micro-organisms	CFU/m^3[c]	1000[d]	1000[d]

[a]Relative humidity shall be within the range of 25–75 percent.
[b]In no case shall the O_2 partial pressure be below 15.0 N/m^2 (2.3 psia) or the O_2 concentration exceed 23.8 percent of the total pressure.
[c]Colony Forming Units (CFUs).
[d]These values reflect a limited base. No widely sanctioned standards are available.

pressure as well as O_2 partial pressure requirements. In spacecraft atmospheres, monitoring of O_2 partial pressure and total pressure is a requirement.

The AR subsystem group conditions the air as necessary to provide a safe and habitable environment for the crew. Monitoring and control of atmospheric trace contaminants and odor are provided, as well as the removal of CO_2. The reduction of CO_2 and generation of O_2 are optional, depending on the level of closure desirable. Atmospheric trace contaminants and odors must be controlled, as necessary, to prevent crew exposure to levels exceeding maximum allowable concentrations. Crew generation of CO_2 during nominal periods is 1 kg/man-day. Breathable quality O_2 is supplied for metabolic makeup at a rate to meet use demands. The nominal use rate of O_2 is 0.83 kg/man-day. The trace contaminant level is controlled at or below the Spacecraft Maximum Allowable Concentration (SMAC).[6] Where near-real-time trace contaminant readings are necessary, sensors must be capable of detecting the SMAC for each constituent at accuracies within ±50 percent.

The WRM subsystem provides the collection, storage, and dispensing of water to meet crew and selected other needs.

Table 5 Nominal crewmember and cabin water balance, nonextravehicular activity (kg/man-day) (general requirements for U.S. crewmembers)

Input		Output	
Crewmember metabolic and food preparation:			
Drink	1.61	Urine	1.50
Food H_2O content	1.15	Sweat and respiration	2.27
Metabolized H_2O	0.35	Fecal H_2O	0.09
Food preparation, liquid	0.79	Food preparation, latent	0.04
Total	3.90	Total	3.90
Cabin:			
Clothes wash	12.46	Clothes wash	
		Liquid	11.86
		Latent	0.60
		Hygiene	
Shower	5.44	Liquid	6.81
Hand wash	1.81	Latent	0.44
Urine flush H_2O	0.49	Urine flush H_2O	0.49
Total	20.20	Total	20.20

Table 6 Water requirements (general standards developed for U.S. crewmembers)

Parameter	Units	Operational	Degraded	Emergency
Potable water	kg/man-day	3.1	3.1	3.1
Wash water	kg/man-day	23.3	9.1	1.4

Water chemical, microbial, and physical control must be accomplished in accordance with accepted standards. Processing of wastewater is optional. Urine, as well as fecal water, may be recovered. Microbial control of water may be accomplished by a number of means. In the United States, iodination is typically required, with an average level of 2 parts per million (ppm) normally used. Distribution services must include both purified water and wastewater. Dispensing must include provisions for the storage and/or disposal of unused waste, such as spent filters, resin beds, and brine recovery residue. Provisions for wet trash and fecal water recovery are optional.

Water thermal conditioning at the use or distribution point may be provided in lieu of central conditioning. Nominal metabolic input and output levels, including water balance, used in the design of Space Station ECLSS are given in Table 5. It should be noted here that food water content dramatically affects the overall water balance and may vary greatly depending on the onboard refrigeration and freezer provisions, crew preference, and medical considerations. Minimum water quantity requirements are given in Table 6, using the current Space Station design as an example. In all water reclamation systems, the capability should exist to recover from upset conditions, especially microbial contamination. On-line water monitoring and control are generally provided for the following parameters: total organic concentration, resistivity, pH, biocide level, turbidity, and temperature.

The WM subsystem provides for the collection, storage and/or processing, and disposal, if necessary, of human waste. This will include considerations of urine, its residue where applicable, and fecal matter. Fecal matter may be compacted and treated (or stabilized), where feasible. Urine will be stabilized and treated with biocide at the collection point where feasible. Urine excreted by a crewmember will nominally be 1.5 kg/day. Typical crew dry fecal matter output is 0.03 kg/man-day. Nominal water expected in fecal matter is 0.09 kg/man-day.

FDS functions include the means for detecting and suppressing fires internal to the pressurized volume. Fire suppressant capability must be restorable after discharge. For multielement or zoned applications, annunciation of fires in any element or zone must be made in all habitable elements or zones. Fire control strategy must include identification of fire location, and both fixed and portable fire suppressant capability must be provided. Sufficient suppressant must be stored onboard to ensure that the worst case and maximum number of fire events can be properly dealt with in a safe and timely fashion. Fires must also be detected early enough to ensure sufficient time either to fight the fire locally or exit the affected element safely while fighting the fire remotely. Where multielement configurations are employed, fire annunciation of a detected event and remote suppression discharge capability to any other element should be employed.

D. Test Verification

The requirements for verification generally are related to the maturity of the program, type of program, previous history of the equipment, and importance or criticality of the equipment. As a result, test requirements may vary greatly. In general, however, most equipment must undergo some form of development, qualification, and acceptance testing. The need for other testing, such as system-level tests, life testing, and prior flight testing, depends on a number of variables. One standard rule is that all items capable of functioning in an Earth environment will be exercised prior to flight.

E. Support to Other Systems

Typically, the ECLSS may provide utility services to other systems. These functions may include services from all ECLSS subsystem groups. For example, the THC subsystem group may provide equipment air cooling to all other systems as well as payloads. The ACS subsystem group may provide gases to the man-system functions (e.g., health monitors) or to payloads. In addition, other attached elements not part of the basic element may be provided by the ECLSS. For example, water or other ECLSS functions could be provided temporarily (e.g., to a transient transfer vehicle) or continuously (e.g., to a continuously docked module).

F. Special Subjects

Safety of the crew is of the utmost importance; consequently, the issue of crew safety in an emergency is of special interest. This condition has been referred to as "safe haven." The allowed environment during safe haven typically may be more relaxed than that required in the normal operating mode (Table 4), especially the life support parameters. Another source of special design requirements is the presence of animals in the pressurized volume in which the crew is also located. Separation of animal ECLSS function responsibilities must be carefully executed between the animal enclosure design and the ECLSS. Another example of special requirements might be the isolation of payload contaminants from the pressurized atmosphere. This is especially important when the payload complement utilizes toxic substances in its equipment. In this event, it is advisable to require a payload containment vessel design with dual-failure tolerance.

The determination of the correct closure approach is again mission-scenario dependent. In the case of a design, such as a small surface lander from a planet orbiting vehicle, a short-duration rover, or an Earth-to-Moon transfer vehicle, where mission times are short, an open-loop design will be indicated. However, in a longer duration flight, such as a planetary mission or a permanent planetary base, a closed-loop design may be more attractive. Other topics of interest are reliability and maintenance. Although optimization of these features is always desirable, it will be appropriate to specify them more rigorously on long-duration flights.

III. The Potential Role of In-Situ Resources for Life Support

The duration of mission, crew size, and distance from the Earth are the key parameters in determining the cost of human exploration of outer space. One way to reduce the cost of a mission is to provide a self-sufficient life support system with no resupply from Earth. In order to achieve this goal,

1) Mission closure of the life support system functions with the help of various regenerative support technologies is required.

2) Utilization of in-situ resources may be needed to produce products and by-products that can be used for life support, power, and propulsion.[7,8]

A. Extraterrestrial In-Situ Resources

The continuous supply of four important elements—carbon, O_2, hydrogen, and N_2—is needed for a self-sustaining life support system. The recovery and availability of these elements from various extraterrestrial in-situ resources are required to provide 0.9 kg/man-day of O_2, 25 kg/man-day of water, 0.6 kg/man-day of dry food, energy, and other expendable materials.[9]

Figure 1 illustrates the fact that regolith, subsurface, polar caps, atmospheric gases of extraterrestrial bodies, and solar energy are five major in-situ resources available in outer space. The resources in the regolith are concentrated in two different particle size ranges. The solar-wind-implanted particles of size below 20 μm are rich in hydrogen and N_2.[10] The particles larger than 20 μm are oxides of aluminum, calcium, chromium, iron, sodium, silicon, titanium, etc.[11,12] A useful by-product of regolith processing may be the possible generation of propellants, such as silane,[13] and recovery of uranium and thorium for thermoelectrical nuclear power plants.[14]

The availability of water is an important issue in planning the human exploration of outer space. Although O_2 is plentiful in the lunar and martian regolith, water and hydrogen are very scarce. The abundance of water in outer space is not well understood; however, it is anticipated that frozen water

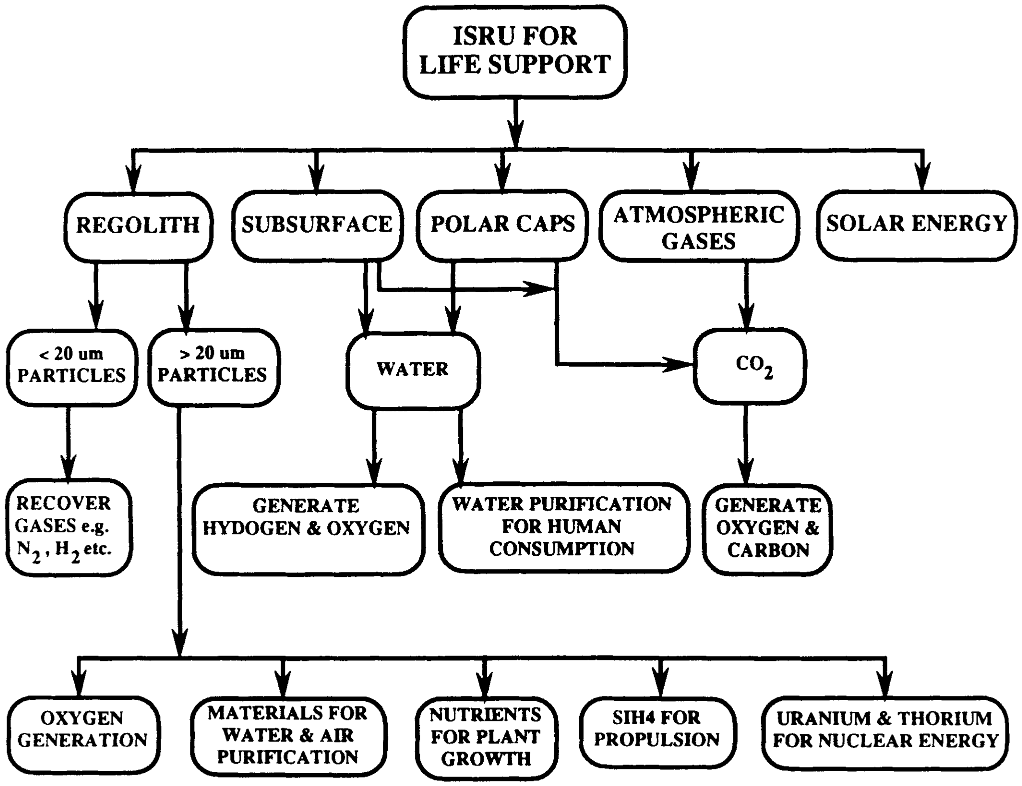

Fig. 1 In-situ resources in outer space.

and CO_2 are available at the subsurface and polar caps of Mars and on both moons of Mars, Phobos, and Deimos.[15,16] CO_2, along with small amounts of water vapor, N_2, and argon, is also available in the atmospheric gases to produce O_2 for life support.

B. In-Situ Resources on the Moon and Mars

There are a number of important in-situ resources available on the lunar surface:

1) The lunar regolith of particle sizes greater than 20 μm: The element composition data for the lunar regolith obtained from several locations are shown in Table 7.[11]

2) The lunar regolith of particle sizes larger than 20 μm: The concentration of hydrogen implanted from the solar wind varies from 124–184 ppm at a depth above 150 cm to 84–104 ppm below that depth.[17] A range of 17–106 ppm hydrogen in 17 bulk soil samples from all Apollo missions was reported.[18] The other solar-wind-implanted gases in the lunar fine are helium (0.5 g/g H_2), helium-3 (0.0002 g/g H_2), neon (0.05 g/g H_2), and argon (0.01 g/g H_2). For every gram of hydrogen recovered from lunar fines, 1.7 grams of N_2 are produced.

3) Extraction of nutrients from lunar soil to support agricultural activities is an area that requires more research. Table 8 presents a comparison of the concentration of essential nutrients needed for plant growth and the concentration of nutrients available in the lunar soil.[19]

4) For more advanced lunar settlements, the thorium and uranium available in the lunar soil may be recovered to produce nuclear fuel to provide energy.

5) Since lunar soil is rich in O_2 and minerals (Table 7), propellants, such as liquid O_2, liquid hydrogen, and silane, also have potential for being manufactured on the Moon.

The important in-situ resources available on the Mars surface are as follows:

1) Martian soil, like lunar soil, is rich in O_2 and minerals.[20]

2) The atmospheric gases of Mars are rich in CO_2.[8]

3) It is believed that large quantities of frozen water and CO_2 are available at the martian polar caps.[15] Similarly, the presence of large quantities of frozen water and CO_2 is also projected on two martian moons, Phobos and Deimos.

4) Sunlight is available 24 h/day.[8] This is an important in-situ resource for the operation of energy-intensive regenerative life support technology.

5) Martian soil, like lunar soil, provides a raw material to produce micronutrients for plant growth.

6) Propellants, such as liquid hydrogen, liquid O_2, and silane, may also be produced from martian resources.

C. In-Situ Resource Utilization (ISRU) Technologies

Recovery of O_2 and other materials from regolith, recovery of hydrogen and N_2 from fine regolith, recovery of potable water from polar caps and the subsurface, generation of O_2 from water and CO_2, production of propellants, genera-

Table 7 Elemental composition of lunar regolith[11]

Element, %	Source of Regolith									
	Mare					High		Basin		
Al	7.29	5.8	7.25	5.46	8.21	14.3	12.2	9.21	9.28	10.9
Ca	8.66	7.59	7.54	6.96	8.63	11.2	10.0	7.71	6.27	9.19
Cr	0.21	0.31	0.24	0.36	0.2	0.07	0.1	0.15	0.19	0.18
Fe	12.2	13.6	12.0	15.3	12.7	4.03	5.71	10.3	9.0	6.68
K	0.12	0.06	0.22	0.08	0.08	0.09	0.06	0.46	0.14	0.13
Mg	4.93	5.8	5.98	6.81	5.3	3.52	5.59	5.71	6.28	6.21
Mn	0.16	0.19	0.17	0.19	0.16	0.05	0.08	0.11	0.12	0.08
Ma	0.33	0.26	0.36	0.23	0.27	0.35	0.26	0.52	0.31	0.3
O	41.6	39.7	42.3	41.3	41.6	44.6	44.6	43.8	43.8	42.2
P	0.05	0.03	0.14	0.05	0.06	0.05	0.05	0.22	0.07	0.06
S	0.12	0.13	0.1	0.06	0.21	0.06	0.08	0.08	0.08	0.06
Si	19.8	18.6	21.6	21.5	20.5	21.0	21.0	22.4	21.7	21.0
Ti	4.6	5.65	1.84	1.29	2.11	0.34	0.29	1.02	0.79	0.97

tion of electrical energy, and production of food are seven major functions that could be utilized to produce materials for life support.

For producing O_2 and other materials from regolith, the regolith may be magnetically processed to separate pyroxene and olivine, followed by electrostatic processing to separate anorthite from ilmenite. In hydrogen reduction processing, ilmenite is reduced in the presence of hydrogen at 923–1273 K. Water is further electrolytically processed to produce hydrogen and O_2. The by-products are iron and titanium dioxide.

In the magma electrolysis process, ilmenite is melted at 1640 K and then electrolyzed to produce O_2. The by-products are iron and titanium dioxide. In the carbochlorination process, anorthite, along with carbon and chlorine, is reacted at temperatures in the range of 848–1043 K. The gaseous metal chlorides, along with carbon monoxide (CO), are passed through a series of condensers. The first condenser removes aluminum trichloride at 363 K, and the second condenser removes CO from silicon tetrachloride and calcium chloride salts at 243 K. The CO is further processed in a Bosch reactor and water electrolysis units to produce O_2.

In a carbothermal process, the magnesium silicate part of the beneficiated regolith is reacted with methane at 1878 K. Water is electrolyzed to produce O_2 and hydrogen. The magnesium oxide and silicon are by-products of this process. In an acid leach process, the mare regolith (unbeneficiated) is processed with hydrofluoric acid at 283 K. The electrolysis of water and iron hexafluorosilicate produces O_2. Silicon tetrafluoride is processed to recover hydrogen fluoride. The by-products are iron, aluminum, magnesium, calcium oxide, and titanium dioxide. In a vapor-ion distillation process, regolith is vaporized and ionized, followed by selective condensation to obtain products as shown: O_2: 54 K; aluminum: 923 K; titanium: 1943 K; iron: 1890 K; and magnesium: 922 K.

Hydrogen may be produced from regolith fines through the use of microwave energy to heat the regolith to 873–1273 K to release adsorbed hydrogen from the materials.[21] Water could be produced from frozen polar caps and subsurface reservoirs, with additional processing to produce potable quality water. The membrane-based reverse osmosis and the adsorbent-based multifiltration are the technologies most commonly used for water purification.[22] To generate O_2 from water and CO_2, the static feed water electrolysis and solid

Table 8 Comparison of essential plant growth nutrients and lunar regolith availability

Nutrients	Plant concentration, percentage weight	Lunar concentration, percentage weight
Carbon	18	0.011
Hydrogen	8	0.0055
Oxygen	70	40
Nitrogen	0.3	0.01
Phosphorous	0.07	0.4
Potassium	0.3	0.4
Calcium	0.5	9.0
Magnesium	0.04	6.0
Sulfur	0.07	0.5
Iron	0.01	9.0
Manganese	0.001	0.2
Boron	0.001	0.002
Molybdenum	0.00001	0.0001
Copper	0.0002	0.0013
Zinc	0.0005	0.0028
Chlorine	0.02	0.0026

polymer electrolysis are the most commonly used methods for water electrolysis.[22] High-temperature metal oxide membranes may be used to electrolytically reduce CO_2 to O_2 and CO.[22] The membrane provides selective transport of ions, thus facilitating the separation of O_2 from CO. Propellants such as O_2 and hydrogen could be cryogenically liquefied to produce liquid hydrogen and O_2.

Photovoltaic methods are a prime candidate to produce electricity on Mars, since adequate sunlight is available. On both the lunar and martian surfaces, the combination of photovoltaics and regenerative fuel cells is a candidate for electrical energy generation. Membrane-based and alkaline fuel cell systems may be used for the generation of electricity. The possibility of using in-situ thorium and uranium as nuclear fuel also exists. However, electrical power generation using space-derived nuclear fuels has yet to be demonstrated to be feasible.

D. In-Situ Resource Usage (ISRU) for Extra-Terrestrial Habitats

The significant in-situ resources available on the lunar surface for physical-chemical life support systems are lunar regolith for O_2 generation and solar energy for power generation. The systems for mining lunar regolith and processing it to generate O_2 have yet to be developed. Therefore, it is unrealistic to predict weight savings in physical-chemical life support systems that could be achieved by lunar regolith utilization. Such predictions would have to trade the weight of mining and processing equipment against that of the life support system.

Mars is an excellent site for ISRU. It is a source of O_2, N_2, hydrogen, CO_2, and water, in addition to available solar energy. For a Mars expedition mission, it is conceivable that a physical-chemical life support system could function almost totally from ISRU. A major contributor to the total life support system weight, the weight of the storage subsystem (consumables and makeup supplies), could be drastically reduced with the help of ISRU technologies.

IV. Reliability of Physical-Chemical Life Support Systems for Long-Term Nonresupply Missions

A. Overview

Future human space missions will require the development of physical-chemical life support systems capable of sustaining future astronauts in space for much longer durations than

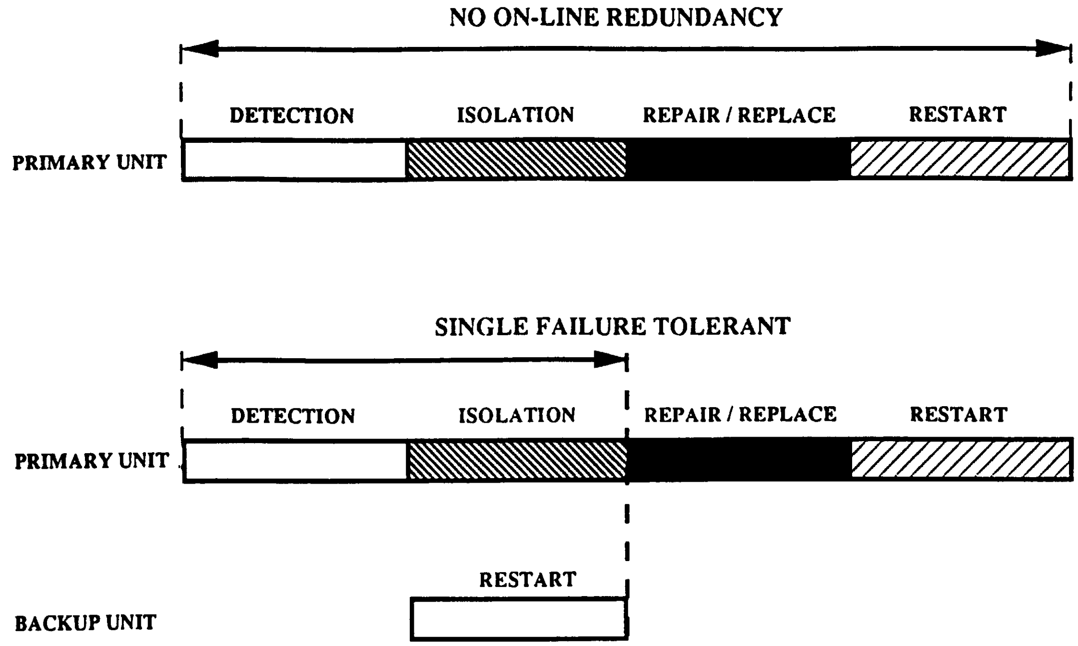

Fig. 2 Time to recover from a fault: No redundancy vs. single failure tolerance.

previous missions. Since the emphasis in these missions will likely be directed away from orbit above the Earth to permanent lunar or planetary bases or interplanetary flights, the next generation of life support systems must provide highly reliable service while meeting weight, power, volume, resupply, and cost constraints. Although life support systems for lunar or planetary bases will evolve to make the best use of available resources, transfer vehicles designed to ferry astronauts to and from these remote outposts may use ECLSS technology first developed for Space Station and Mir. Based upon flight experience with the Space Station and Mir programs, repair and redundancy strategies should be well established for long-term space endeavors. A conceptual life support system with estimates of space weight and repair and redundancy strategies is presented.

B. Statement of the Problem

The mission parameters for a human mission to Mars are used to derive a set of generic requirements applicable to the development of a long-term ECLSS. Although the duration of a human mission to the outer planets in the solar system would be much longer than for a visit to Mars, requirements governing the development of an ECLSS for an Earth-to-Mars transfer vehicle should be similarly relevant to any interplanetary mission. NASA's 90-Day Study on Human Exploration of the Moon and Mars outlined a plan to establish a lunar outpost and perform a human visit to Mars early in the next century.[23] The lunar outpost, along with Space Station, may be used as a development and staging area for the exploration of Mars. The total round-trip duration for manned visits to Mars early in the next century is expected to range between 500 and 800 days, depending on the trajectory of the vehicle and the stay time in the martian system. Crew sizes for these early missions are expected to be small (four to five astronauts). The only mission resupply identified is a preplanned rendezvous with a cargo vehicle in orbit around Mars. The mission parameters are summarized as follows: 1) mission duration of 1–3 years, 2) no unscheduled or contingency resupply, 3) limited mission abort/rescue options, 4) crew size of four, and 5) design to cost.

The mission duration, as well as the resupply and emergency constraints, will require that the ECLSS be designed within an established reliability requirement. Through analysis and testing, it will have to be demonstrated with a high degree of confidence that the ECLSS can operate satisfactorily over the mission duration. Some hardware will be designed to survive the mission with minimal repair, whereas other components may be replaced several times. Designing to cost may result in the use of life support equipment derived from Space Station and Mir to a large extent. This could minimize development costs and possibly minimize life testing because of the available flight experience. The reliability and maintainability design is key to meeting this requirement, as the number of spares will represent a significant portion of the launch weight.

C. Reliability and Maintainability Design Approach

Central to the design of a life support system for long-term space missions are reliability and maintainability considerations. Repair and redundancy strategies, system data base development, reliability allocations, spare requirements, and life testing must all be addressed to ensure an adequate design. Two basic strategies exist in the design of reliable systems.[24,25] First, a system can be designed to survive a given

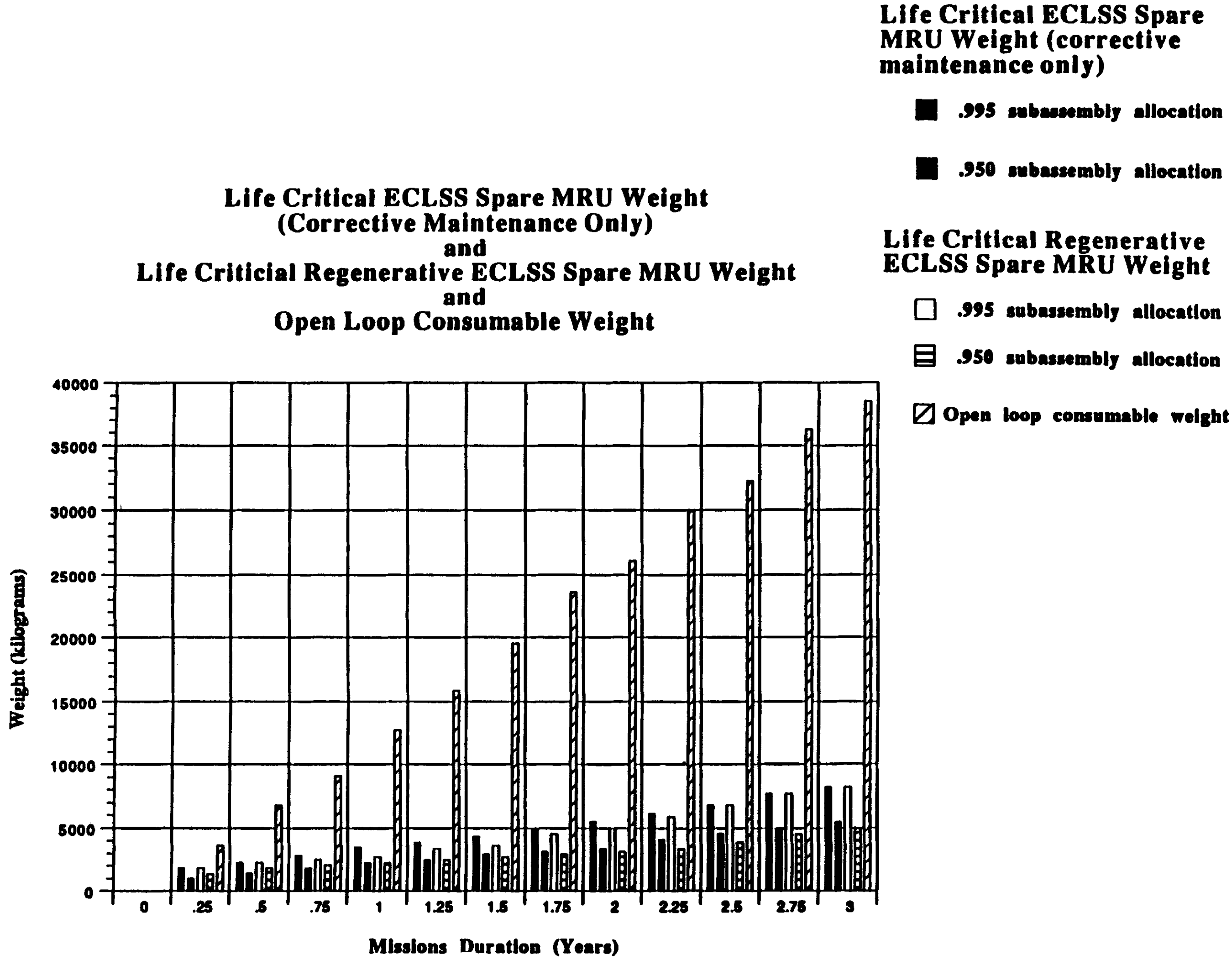

Fig. 3 Estimated weight of life critical ECLSS MRU spares for two reliability requirements as a function of mission duration. Comparison of critical regenerative ECLSS space MRU weight and open loop consumable weight as a function of mission duration.

mission duration with little or no repair. Backup assemblies are available in the event of failure; and, in the case of manned missions, only the most critical spares are provided. A second approach is to design a maintainable system or, in other words, a system that can be restored after failures. The maintainable system approach is more practical for human missions of longer duration where crew intervention is possible. The maintainable system design must account for all of the necessary spares. In this design approach, redundancy is implemented primarily to circumvent the temporary loss-of-time critical functions.

D. Repair and Redundancy Strategy

Future space vehicles will comprise a number of different systems, such as life support, power, propulsion, and data management. Each system can be divided into a number of subsystem groups, with each subsystem group providing several related functions. In the ECLSS architecture, for example, all water reclamation and management functions for the recovery, monitoring, and distribution of potable and wash waters are grouped under one subsystem group. Furthermore, each group is subdivided into a number of subassemblies. In the case of the ECLSS, a subassembly generally provides all or part of a single function, such as CO_2 removal, avionics cooling, or wash water recovery. To facilitate maintenance and repair, each subassembly is further divided into a number of replaceable units and components. Subassemblies are maintained through the replacement of specially defined subcomponents called mission replaceable units (MRUs). Each subassembly is divided into a number of MRUs; MRU selection is optimized against individual mass and predicted failure rate. Other factors influencing MRU selection include the number and type of connections (i.e., electrical, mechanical) and accessibility within the subassembly.[26] Repair below the MRU level is permitted through the use of another replace-

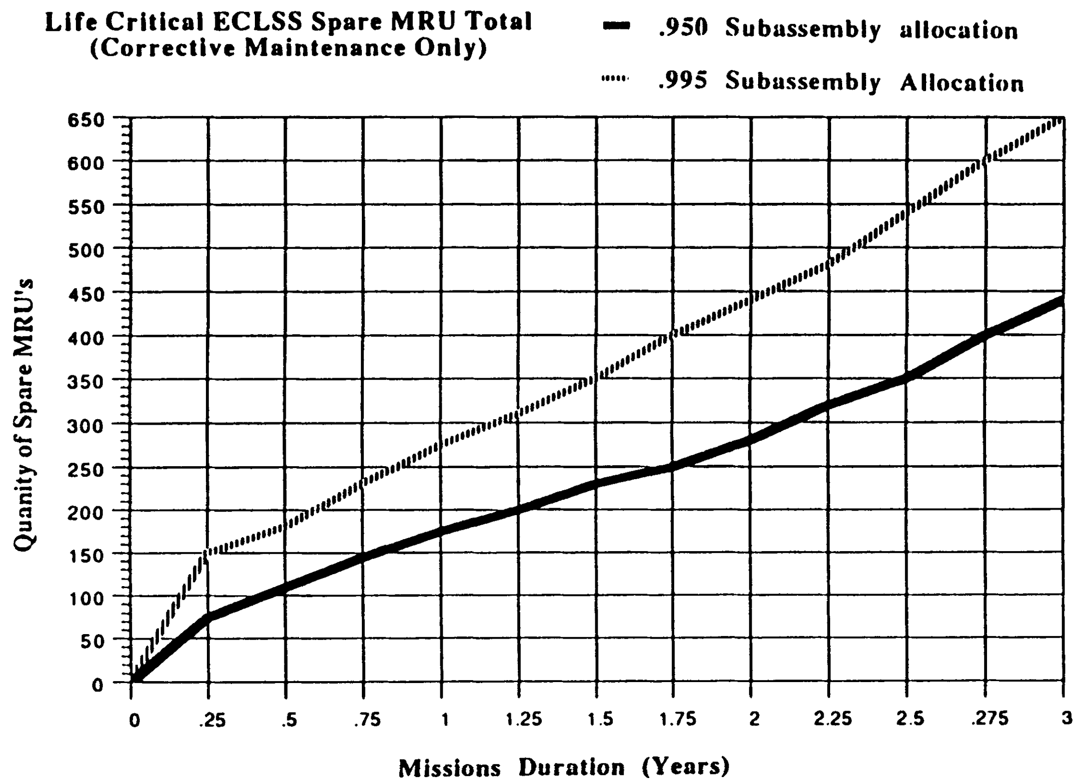

Fig. 4 Estimated total number of life critical ECLSS MRU spares for two different reliability requirements as a function mission duration.

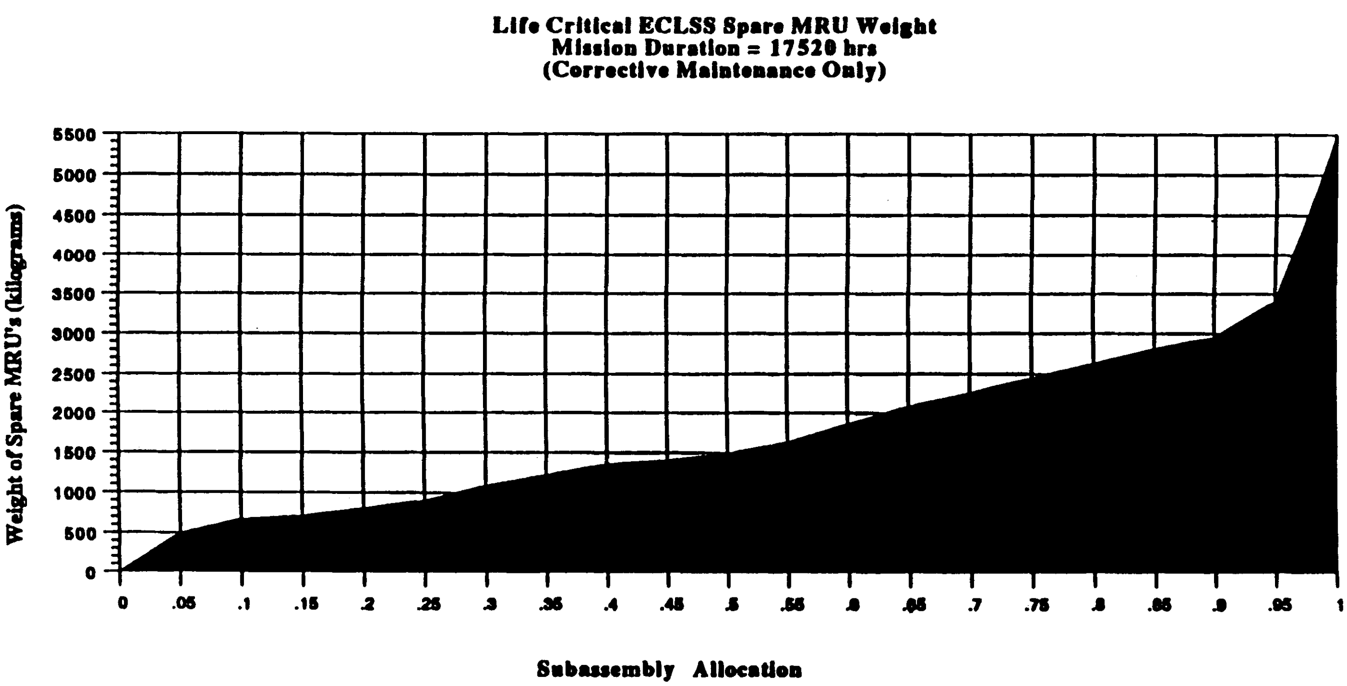

Fig. 5 Weight of life critical ECLSS MRU spares as a function of subassembly reliability allocation for a two year mission.

able subcomponent, called a mission replaceable component (MRC). MRCs allow for the use of common parts, primarily sensors (although others are possible), between MRUs. A failed MRU that would otherwise be rendered useless can be returned to active service through the replacement of a much less complex part, the MRC.

On-line redundancy of life support subsystems will be implemented to minimize the effects of a disruption of service due to failure. The level of failure tolerance will be dependent upon the criticality of the function. Recovery from a failure occurs in four steps: 1) detection, 2) isolation, 3) repair, and 4) restoration. As shown in Fig. 2, the presence of an on-line backup unit can reduce the total recovery time, since the redundant system can be started while the primary one is repaired. The life-critical nature of most ECLSS functions demands at least single-failure tolerance, with dual- or triple-failure tolerance preferred to cover protracted repair times or multiple failures.

E. Reliability Allocations and Spare Requirements

Program reliability requirements for long-term space missions will likely be defined at the system or subsystem level. Through maintenance, the ECLSS will be required to provide service with limited interruption for the duration of long-term space missions. Since the ECLSS is a complex system comprising different subsystems and subassemblies, the reliability and maintainability design approach becomes a question of how to allocate the high-level reliability requirements down to the lowest components in the system. One method would be to envision each high-level component, such as a subsystem or subassembly, as a number of low-level components, such as an MRU, connected in series. The low-level reliability requirements are derived such that the higher level requirement is met. Using the basic laws of probability,[24,25] reliability requirements are applied in succession at the subsystem, subassembly, and MRU levels. Significant resource reductions are possible if low-level reliability requirements are optimized with regard to weight (i.e., a higher reliability requirement should be allocated to a lighter component, such as a sensor, rather than to a heavier component, such as a compressor).

Using this approach and a data base constructed from Space Station reliability and mass property data,[27] estimates of spare weight were computed parametrically for life-critical ECLSS hardware against mission duration and subassembly reliability requirements. For demonstration purposes, each life-critical ECLSS subassembly was assumed to have a reliability allocation of either 0.995 or 0.950, meaning a 99.5 percent or 95.0 percent probability of success over the given mission duration. As expected, the weight of spares required to meet a given requirement increases with increasing mission duration (Fig. 3). Also, the total number of spare MRUs required to meet a given requirement was computed and is shown plotted against mission duration in Fig. 4. The dependence on the subassembly allocation is shown in Fig. 5 as the weight of spare MRUs required to support a mission of 2 years in duration, plotted parametrically against subassembly allocation. Again, the allocation of reliability requirements down to the MRU level was not optimized with regard to individual MRU weight. Weight savings are possible if heavier MRUs are allocated a lower requirement whereas lighter MRUs are designed to a more stringent requirement.

In light of the apparent excessive weight of spares needed to support a regenerative ECLSS, a comparison against consumables required for an open-loop ECLSS is shown in Fig. 3. The weight of the consumables is based upon a crew size of four and assumed requirements of 2.6 kg/man-day of drinking water, 5.4 kg/man-day of wash water, and 0.8 kg/man-day of O_2. Although the weight of tankage is not included in the comparison, the regenerative system shows a clear advantage in launch weight. The installed weights of both systems, as well as other penalties, such as power, would have to be addressed for a complete trade.

F. System Data Base

A reliability and maintainability data base is essential to the design of long-term ECLSSs. Reliability and maintainability data, such as component failure rates and mean time to repair (MTTR), will be used in system design trade-off and analyses, along with weight, power, and volume estimates. Future ECLSS data bases will make extensive use of Space Station and Mir flight experience, as well as aircraft and submarine data. As system development progresses, the data base will be continually updated and validated against ground test data.

The data base will likely be organized at the MRU level. Each MRU field will contain entries for a predicted failure rate mean time between failures (MTBF) and MTTR. The MTTR projections will reflect the actual time required to remove and replace an MRU with an identical MRU, as this will be the normal method of repair. The MTTR will account for such factors as number of connections, connector type (i.e., electrical and/or mechanical), and MRU accessibility within the subassembly.[26] The data base will also contain entries for the MRU duty cycle and estimates for the MRU weight and volume. The weight and volume entries will be used to support logistics analyses to determine the total launch weight and volume of spares required for a mission of given duration. The data base may also include entries to indicate the changeout frequency of consumable MRUs, such as particular filters or sorbent beds.

A number of data base entries will be quantities derived from information contained elsewhere in the data base. Key among these will be estimates for the number of spare MRUs. As illustrated earlier, system reliability requirements will be allocated to the MRU level. The estimates for crew maintenance hours are computed from the individual MRU failure rates and MTTR predictions.[26,27] As crew time is a critical resource like weight or power, the ECLSS design must ensure that an inordinate amount of time is not consumed for

Table 9 Example ECLSS Data Base

Mission duration	17,520 h
Subassembly reliability goal	0.995

MRU description	Subsystem	Subassembly	Qty.	Unit mass, kg	Total mass, kg	MTBF, h	Failures 10^6,h	Allocation	Total units	Spare units	Spare mass, kg
Water separator	THC	Cabin	1	7.26	7.26	38,183	26.190	0.9992	7	6	44.20
Cond. heat exchange	THC	Cabin	1	17.83	17.83	100,000	10.000	0.9992	4	3	51.29
Temperature sensors	THC	Cabin	1	1.81	1.81	150,000	6.667	0.9992	3	2	4.02
HEPA filter	THC	Cabin	1	6.80	6.80	832,639	1.201	0.9992	2	1	5.65
Check valves	THC	Cabin	1	6.80	6.80	620,732	1.611	0.9992	2	1	6.66
Cabin fan	THC	Cabin	1	19.32	19.32	41,752	23.951	0.9992	7	6	108.57
Totals			6	59.83	59.83	14,364[a]	69.62				220.39

[a]Mean time before failure for total system derived from test data and is not a total of numbers appearing above it in the column.

maintenance when compared to other activities. An example data base is provided in Table 9.

G. Life Testing

A test program must be implemented to qualify the long-duration ECLSS before flight and to validate and/or partially generate the reliability and maintainability data base used in the design of the system. Life testing of subassemblies and lower components will be used to validate predicted component failure rates contained in the ECLSS data base or to obtain new failure rates where existing data are nonexistent or suspect. Additional tests using form and fit mockups or flight quality hardware may be conducted to validate MTTR predictions.

The keys to implementing a successful life test program are determining the number of trials necessary to establish the average failure rate of a given subassembly or MRU and deciding which subassemblies or MRUs to test. Obviously, resources to conduct extensive life tests on every component in the system will not be available. It will be necessary, through similarity or existing flight data, to waive life testing on some components in the system. Extensive flight data will likely exist for a number of ECLSS components, including air and liquid heat exchangers, fans, and sorbent beds. Of course, new technologies with no previous flight experience will receive high priority for ground testing to substantiate failure rate predictions contained in the engineering data base.

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